Future Measurement of $\sin^2 2\theta_{13}$ at Nuclear Reactors

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Introduction

U_{e3} is the only element of the MNS matrix yet to be measured

<0.12 (CHOOZ & Palo Verde)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \sim 0.7 & \sim 0.7 & \sin\theta_{13} e^{i\delta} \\ \sim -0.5 & \sim 0.5 & \sim 0.7 \\ \sim 0.5 & \sim -0.5 & \sim 0.7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U_{e3} is important because it sets the scale for CP violation in the lepton sector.

Δm_{13}^2 is known from atmospheric ($\Delta m_{13}^2 = \underbrace{\Delta m_{23}^2}_{\text{Atmospheric}} + \underbrace{\Delta m_{12}^2}_{\text{Solar}} \approx \Delta m_{23}^2$)

If know your neutrino energy you know where to put your detector to optimize oscillations.

$\mathrm{Sin}^2 2\theta_{13}$ can be investigated with Accelerators and/or with Reactors

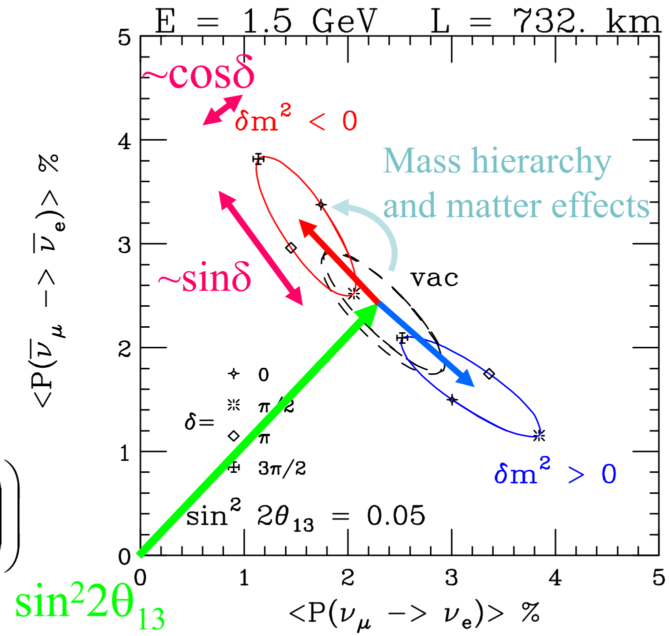
Methods of Measuring $\sin^2 2\theta_{13}$

1. Measure with an Accelerator
   (JHF-SK and NuMI Off-axis)
   - Appearance $\nu_\mu \rightarrow \nu_e$ (or $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with separate running)
   - Off-axis to have a monochromatic ν_μ beam
   - Long Baseline (300 – 900 km)
   - Very large detector

⃠ $\sin^2 2\theta_{13}$ is not independently measured – parameter degeneracy
(CPV phase δ, matter effects and mass hierarchy)

See talks by H. Minakata, H. Sugiyama and W. Winter in WG1

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) +$$
$$\boxed{\frac{\Delta m^2_{21}}{\Delta m^2_{31}}} \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \times$$
$$\left(\mp \sin\delta_{CP} \sin^3\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos\delta_{CP} \cos\left(\frac{\Delta m^2_{31} L}{4E}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)\right)$$



Methods of Measuring $\sin^2 2\theta_{13}$ (Continued)

2. Measure at a Nuclear Reactor

(Previous experiments CHOOZ and Palo Verde)

- Baseline ~1 km
- Disappearance $\overline{\nu}_e \rightarrow \overline{\nu}_e$
- Use identical near detector to measure reactor flux, spectrum and detector efficiency to cancel most systematics
- Look for small rate deviation from $1/r^2$ in a large reactor signal
- Direct measurement of $\sin^2 2\theta_{13}$

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{13}^2 L / E_\nu)$$

Combining measurements from these two methods results in the best sensitivity to $\sin^2 2\theta_{13}$ and δ!

See P. Huber WG1 today at16:30

Nuclear Reactors as a Neutrino Source

- Nuclear reactors are a very intense sources of $\bar{\nu}_e$ deriving from the β-decay of the neutron-rich fission fragments.

- Each fission liberates about 200 MeV of energy and generates about 6 neutrinos. So for a typical commercial reactor (3 GW thermal energy)

$$3\text{ GW} \approx 2\times10^{21}\text{ MeV/s} \rightarrow 6\times10^{20}\ \bar{\nu}_e/\text{s}$$

- The observable $\bar{\nu}$ spectrum is the product of the flux and the cross section.

- The reaction process is inverse β decay:

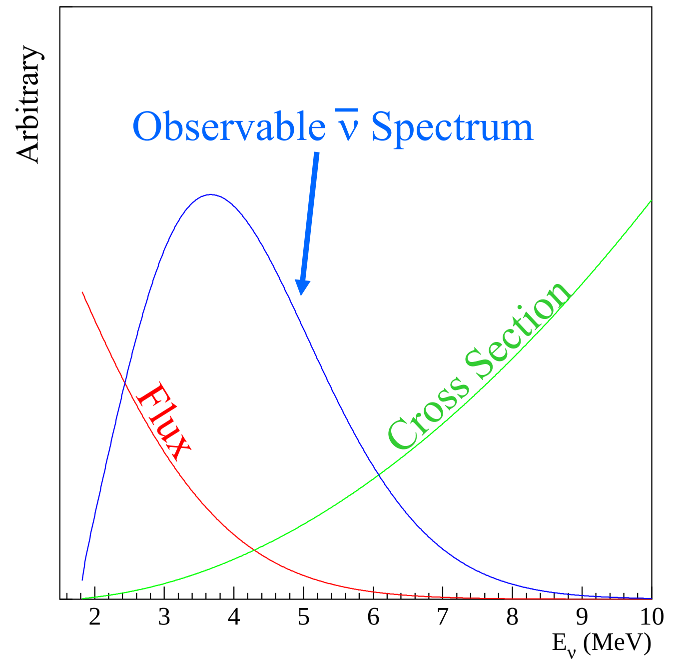
$$\bar{\nu}_e\, p \rightarrow e^+ n$$

~30 μs later

$$\hookrightarrow n\ Gd \rightarrow \gamma\text{'s (8 MeV)}$$

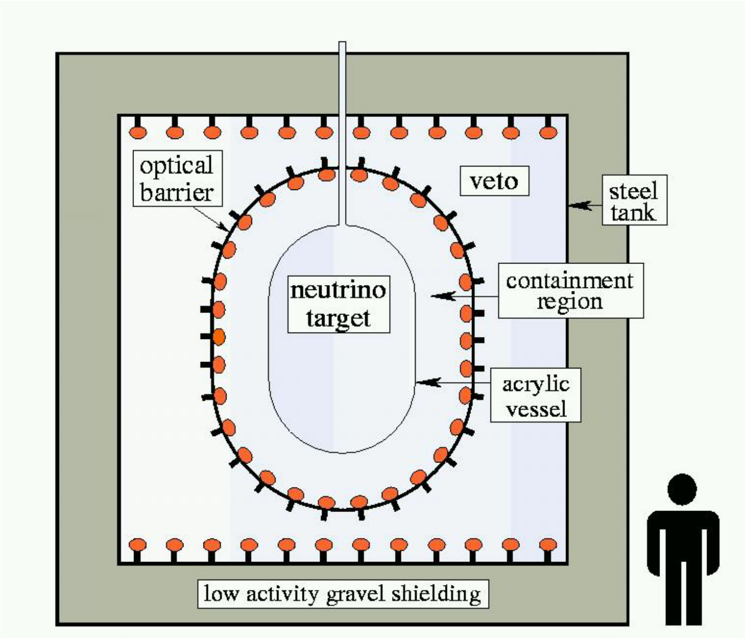
Two part coincident signal

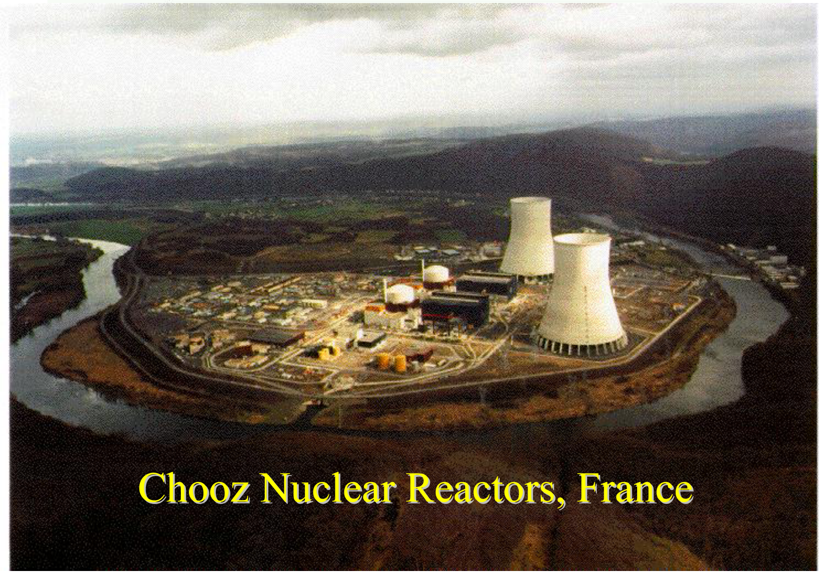
- The spectrum peaks at ~3.7 MeV.



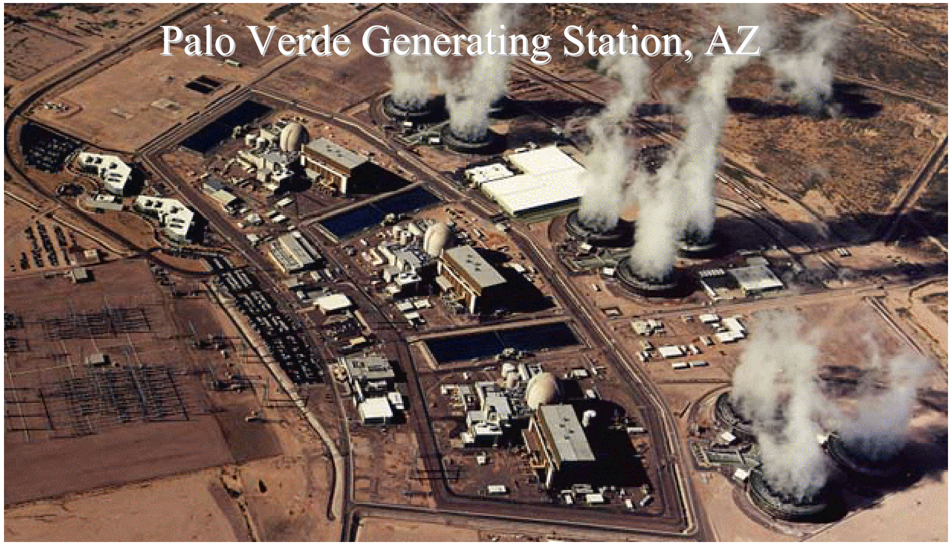
CHOOZ

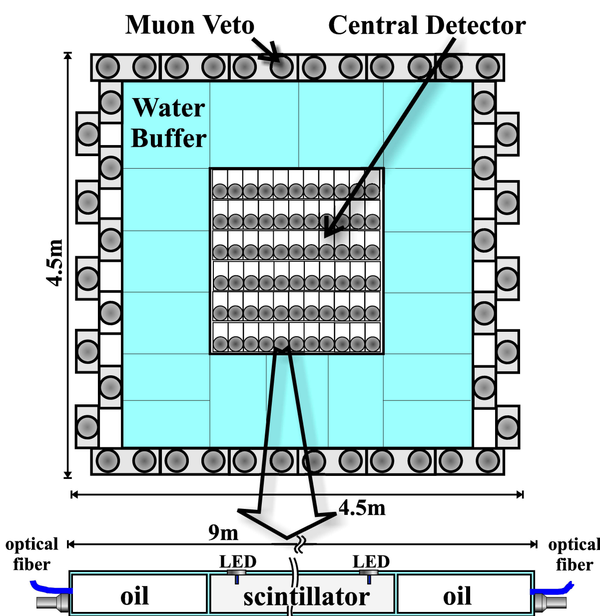
- Homogeneous detector
- 5 ton, Gd loaded, scintillating target
- 300 meters water equiv. shielding
- 2 reactors: 8.5 $GW_{thermal}$
- Used new reactors → reactor off data for background measurement
- Baselines 1115 m and 998 m
- Expected rate of ~25 evts/day (assuming no oscillations)





Palo Verde





- 32 mwe shielding (Shallow!)
- Segmented detector:
  Better at handling the cosmic rate of a shallow site
- 12 ton, Gd loaded, scintillating target
- 3 reactors: 11.6 $GW_{thermal}$
- No reactor off running
- Baselines 890 m and 750 m
- Expected rate of ~50 evts/day (assuming no oscillations)

CHOOZ and Palo Verde Results

- Neither experiments found evidence for $\bar{\nu}_e$ oscillation.

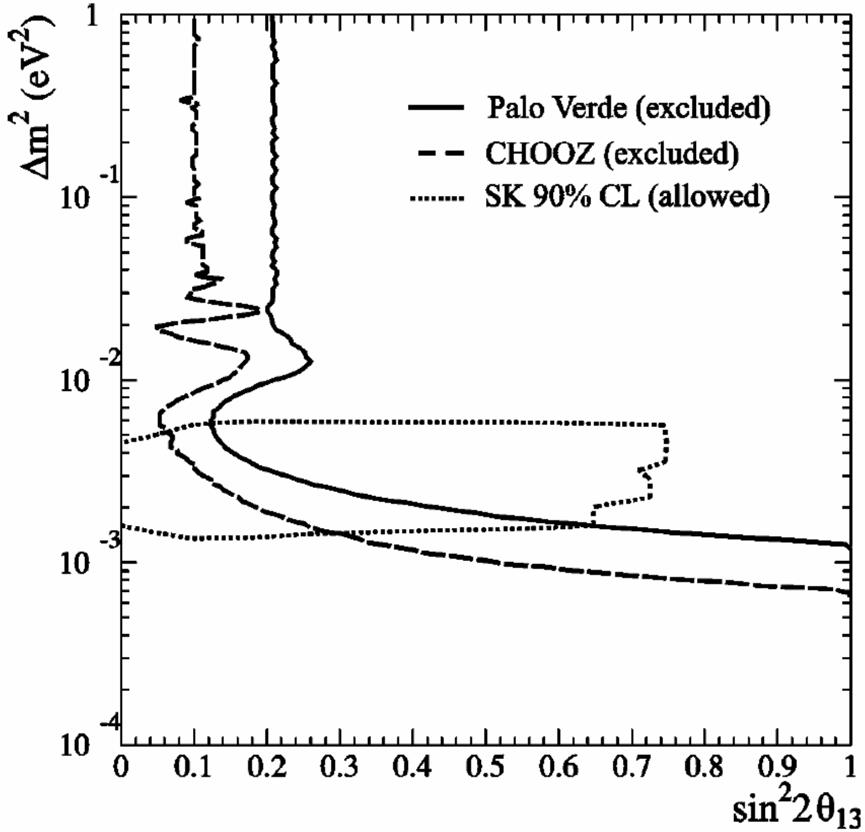
- This null result eliminated $\nu_\mu \rightarrow \nu_e$ as the primary mechanism for the Super-K atmospheric deficit.

- $\sin^2 2\theta_{13} < 0.12$ at 90% CL

- Future experiments should try to improve on these limits by *at least* an order of magnitude.

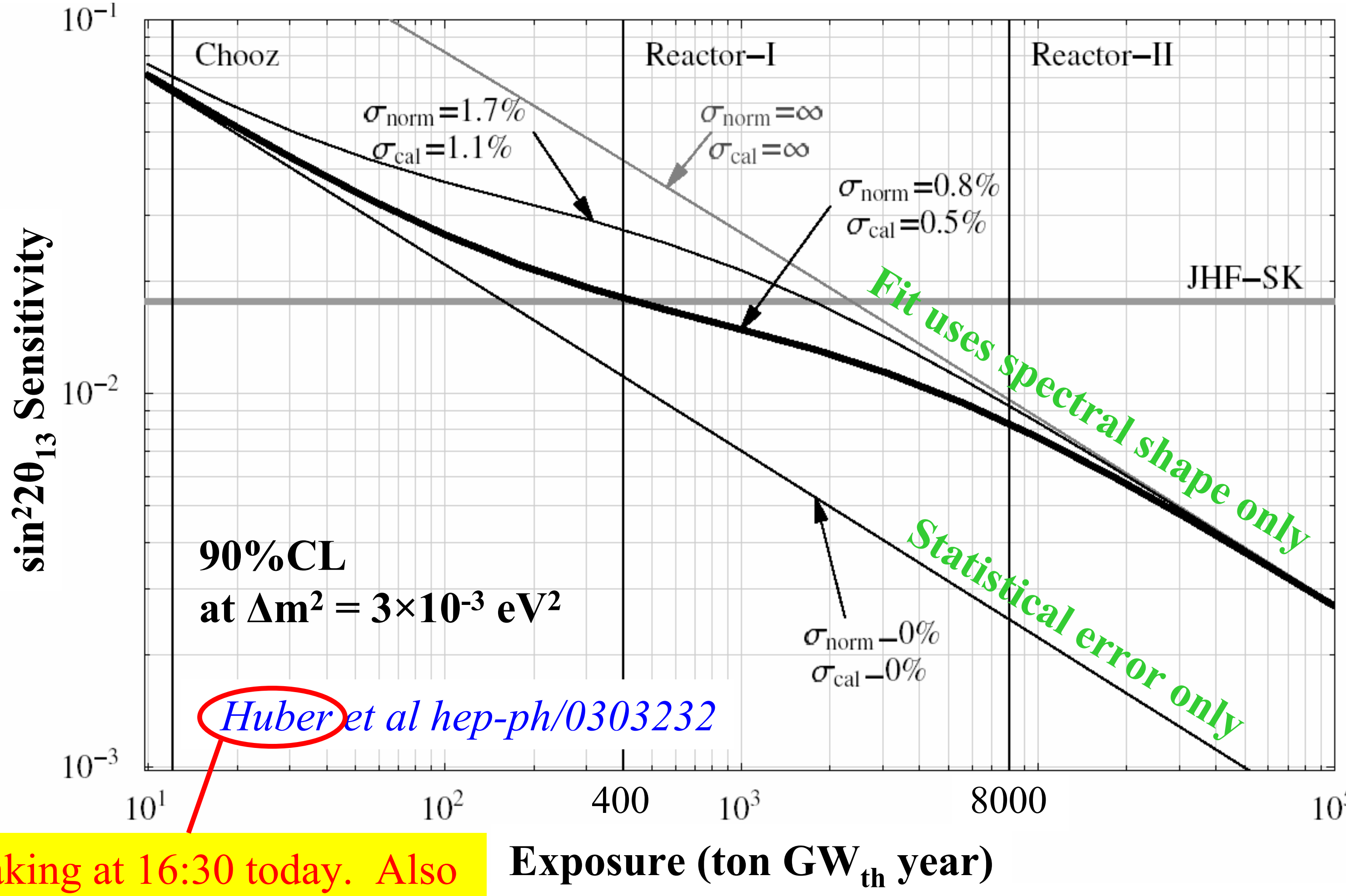
Down to $\sin^2 2\theta_{13} < 0.01$

In other words, a 1% measurement is needed!



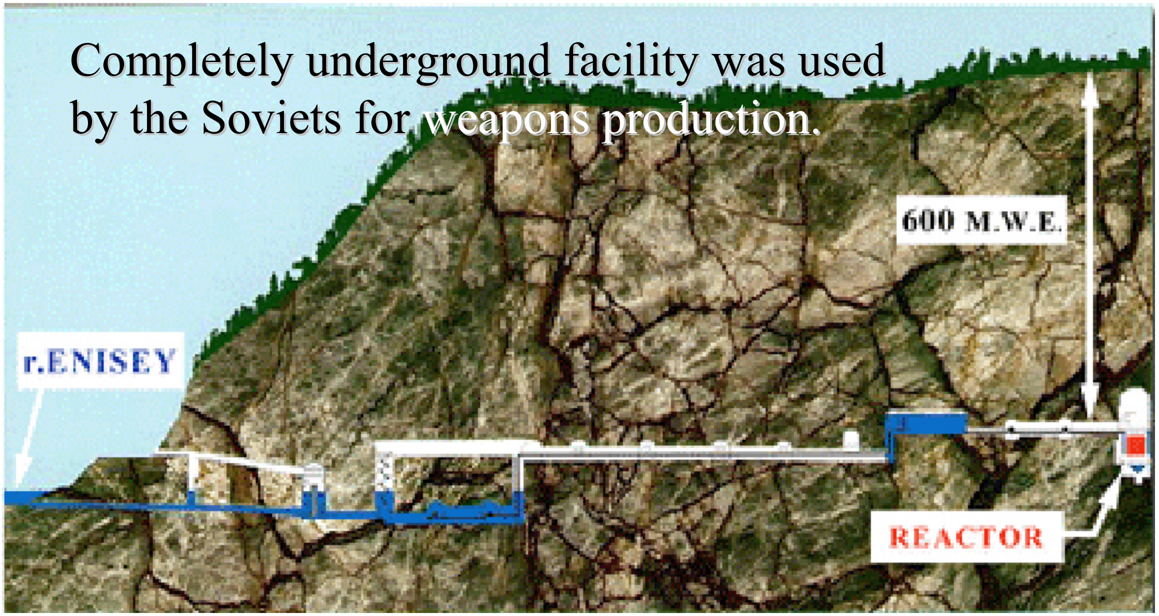
Sensitivity Reach as a Function of Exposure

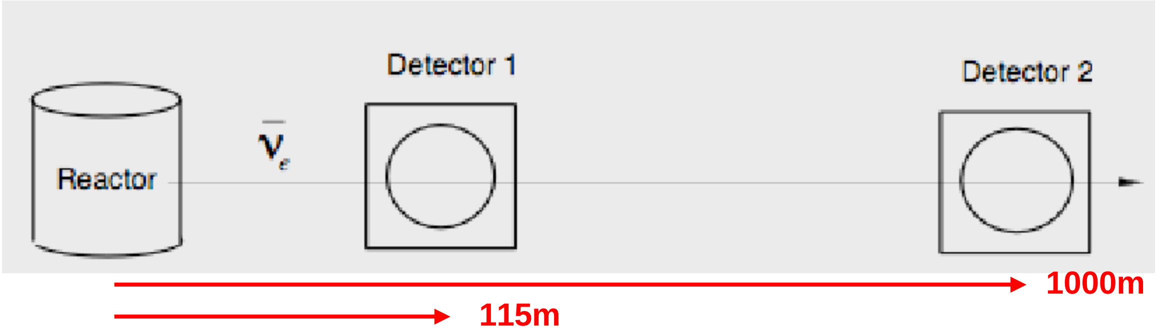
Assumes negligible background; σ_{cal} relative near/far energy calibration
σ_{norm} relative near/far flux normalization



Speaking at 16:30 today. Also W. Winter on Saturday at 17:00

Krasnoyarsk, Russia (hep-ex/0211070)



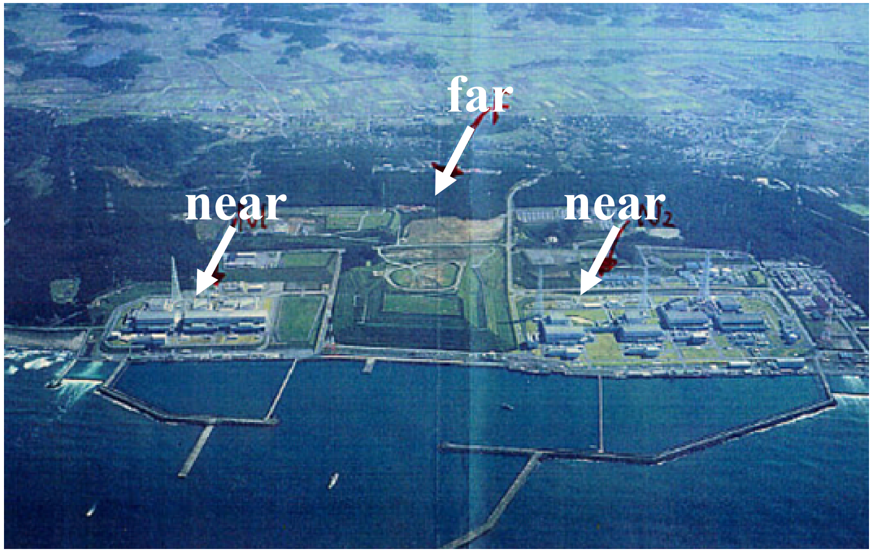


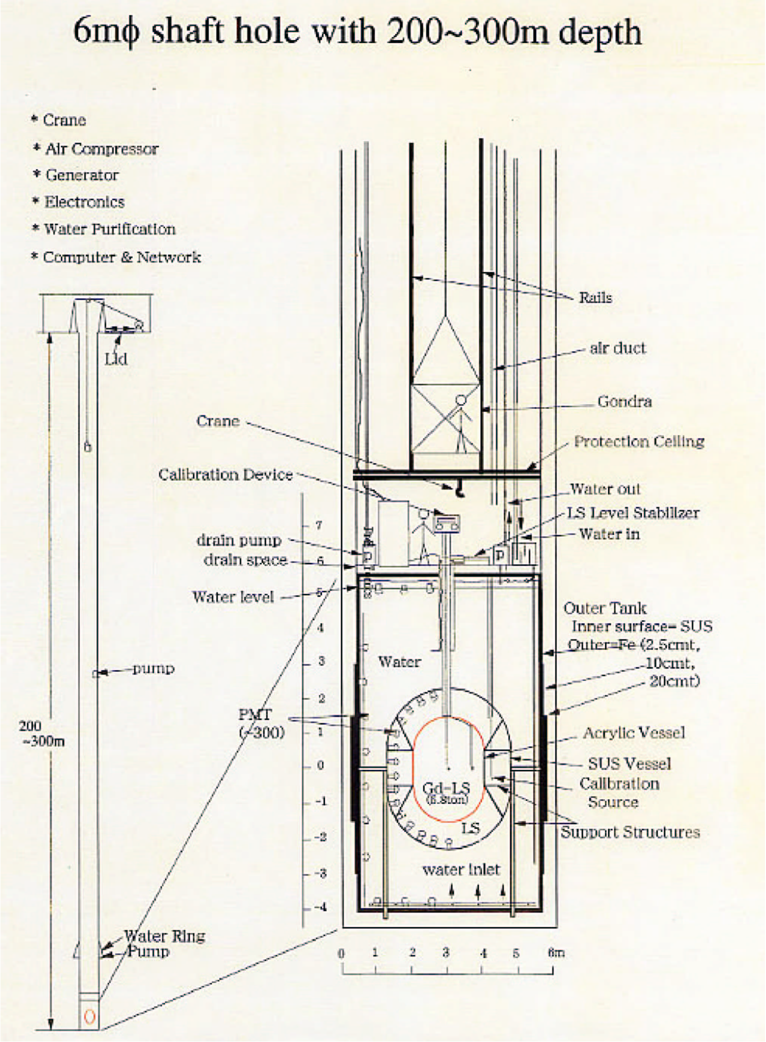
- One ~2 GW reactor
- Two 50 ton detectors
- Near detector at 115 meters
- Far detector at 1000 meters
- About 60 days of reactor off running per year.
- ~100 GW·tons
  (4 years → ~0.02)

Kashiwazaki, Japan (hep-ph/021111)

- 7 Reactors, 24 $GW_{thermal}$ (most powerful site in the world)
- Three ~8 ton detectors
- Two near detectors at baselines of 300 to 350 meters
- One far detector at ~1300 meters
- ~190 GW·tons

See O. Yasuda in WG1 today at 16:00





Possible U.S. Sites

• Most U.S. sites have one or two reactors.

• One and two reactor sites are conceptually easier: only one baseline. (The experiment *can* be done at multi-reactor sites.)

• U.S. two reactor sites are among the best in the world in power performance.

~350 GW·tons (with a 50 ton detector)

• Many U.S. sites have other favorable qualities such as potential for shielding.

The challenge will be getting reactor operators to agree to work with us!

Top 30 U.S. Sites by Power Performance

US Reactor Sites	State	Cores	Avg GW th	Max GWth
Palo Verde	AZ	3	10570	11552
South Texas Project	TX	2	6864	7600
Braidwood	IL	2	6491	7172
Vogtle	GA	2	6456	7130
Byron	IL	2	6442	7172
Browns Ferry	AL	2	6377	6916
Limerick	PA	2	6365	6916
Peach Bottom	PA	2	6290	6916
Sequoyah	TN	2	6209	6822
Oconee	SC	3	6204	7704
Susquehanna	PA	2	6161	6978
Catawba	SC	2	6116	6822
San Onofre	CA	2	6061	6876
Diablo Canyon	CA	2	6043	6749
Comanche Peak	TX	2	5986	6916
McGuire	NC	2	5880	6822
North Anna	VA	2	5129	5786
St. Lucie	FL	2	4925	5400
Edwin Hatch	GA	2	4901	5526
Arkansas Nuclear	AR	2	4844	5383
Calvert Cliffs	MD	2	4813	5400
Joseph Farley	AL	2	4801	5550
Dresden	IL	2	4779	5914
Brunswick	NC	2	4701	5116
Surry	VA	2	4664	5092
Nine Mile Point	NY	2	4500	5317
Quad Cities	IL	2	4481	5914
Indian Point	NY	2	4467	6096
La Salle	IL	2	4323	6978
Salem	DE	2	4281	6918

What is the Right Way to Make the Measurement?

Start with the Systematics and Work Backwards…

CHOOZ Systematic Errors, Normalization

parameter	relative error (%)
reaction cross section	1.9%
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%

Near Detector

Identical Near and Far Detectors

Movable Detectors

CHOOZ Background Error

BG rate 0.9%

μ Veto and Neutron Shield

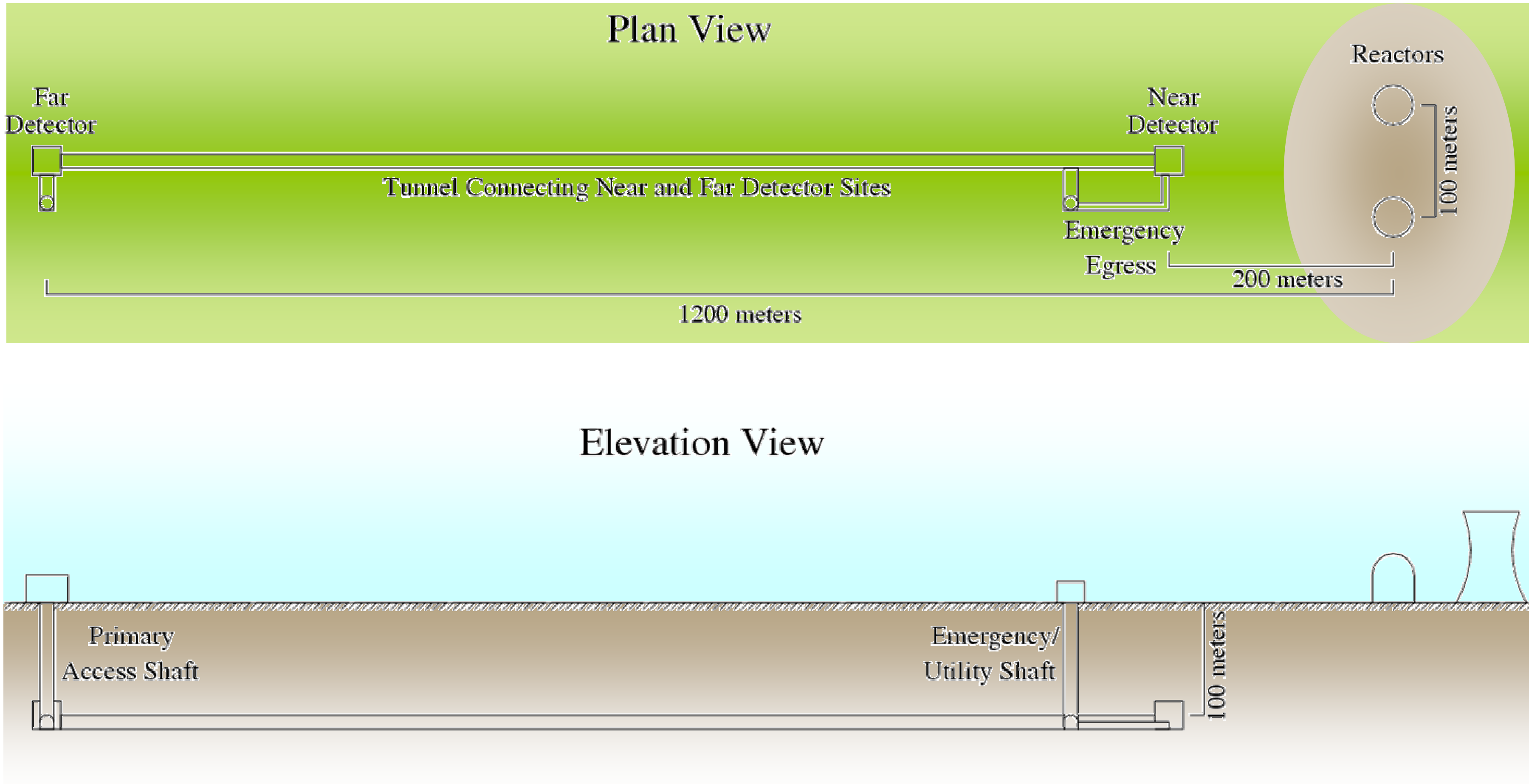
Statistics may also be a limiting factor to the sensitivity.

Movable Detector Scenario

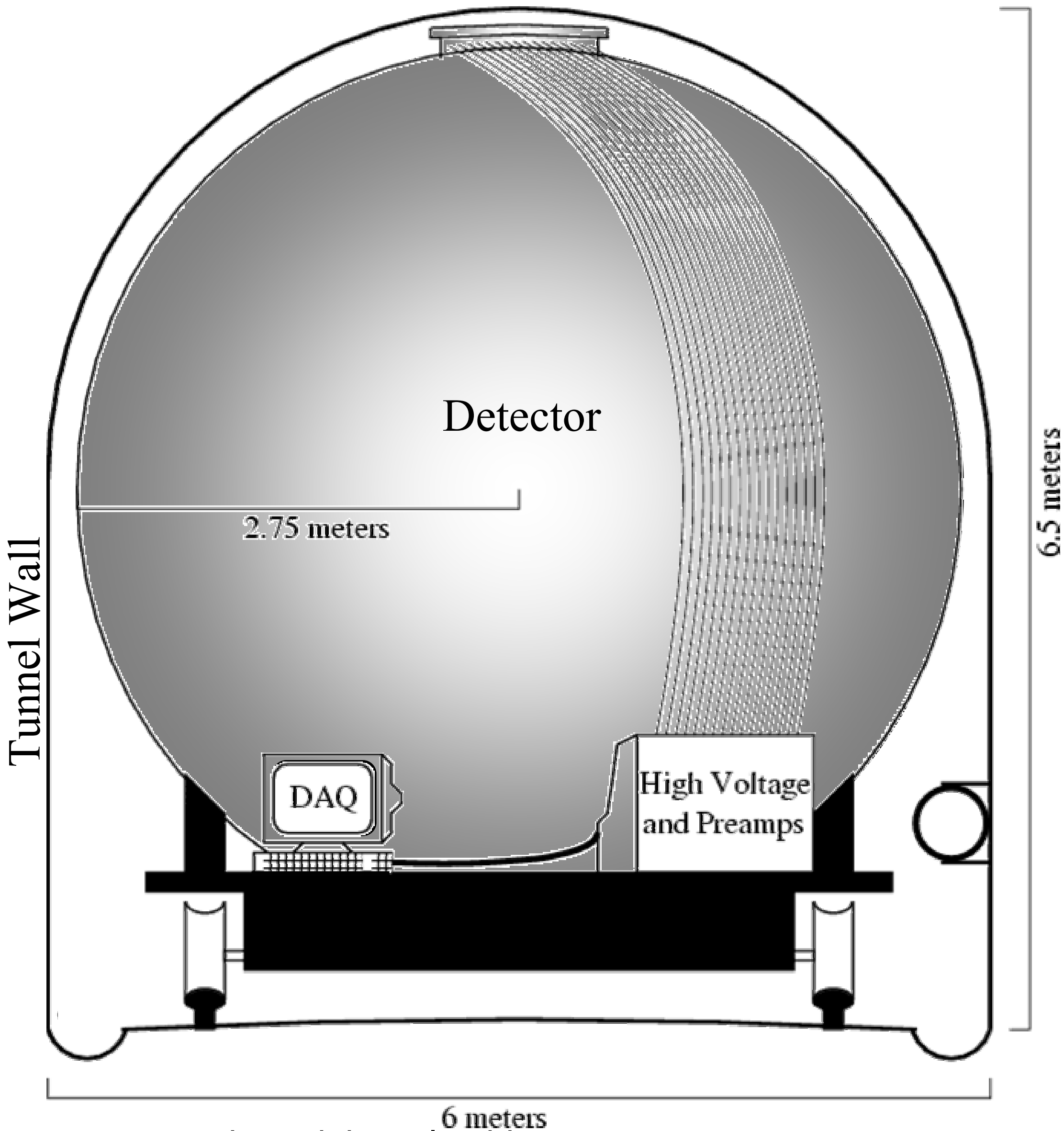
The far detector spends about 10% of the run at the near site where the relative efficiency of the two detectors is measured head-to-head.

The detectors must be well underground to reduce the cosmic rate.

So the near and far sites need to be connected by a tunnel!



Detector Design



Larger version of CHOOZ (smaller KamLAND)

- Homogenous Volume
- Viewed by PMT's
- Gadolinium Loaded, Liquid Scintillator Target
- Pure Mineral Oil Buffer

In the Movable Scenario

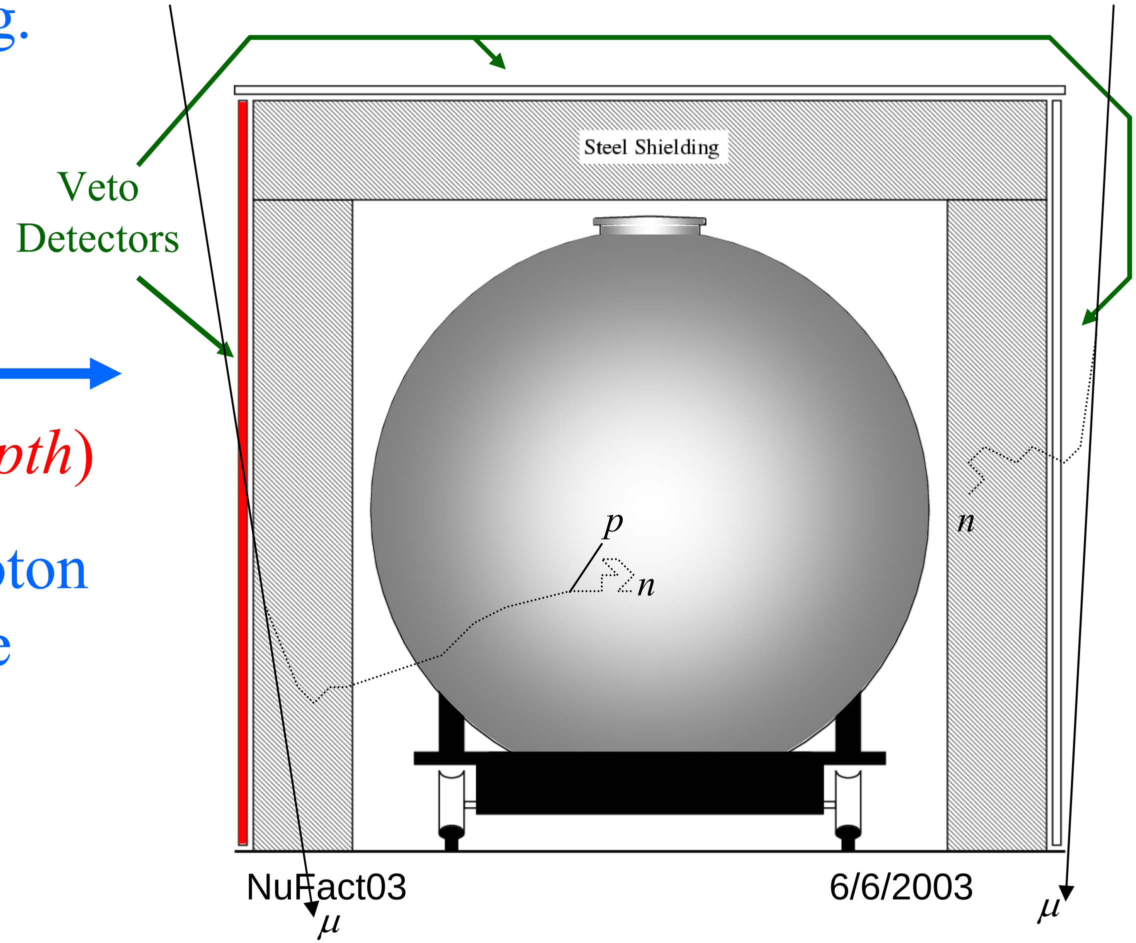
- Rail System for Easy Transport
- Carries Electronics and Front-end DAQ.

Systematic Error from Backgrounds

At sites with more than one reactor there is no reactor off running, so other ways of measuring the backgrounds are needed.

The toughest background comes from fast neutrons created by cosmic μ's. They can mimic the coincidence signal by striking a proton and then capturing.

1. Build it deeper
   (hard to do!)
2. Veto μ's and shield neutrons (*effective depth*)
3. Measure the recoil proton energy and extrapolate into the signal region.



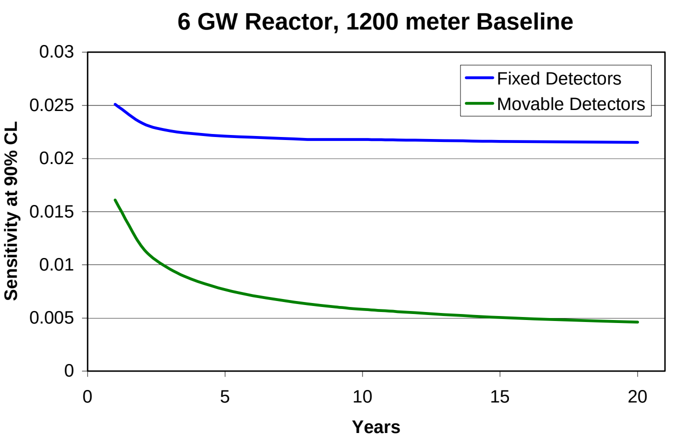
Detailed Optimization Studies

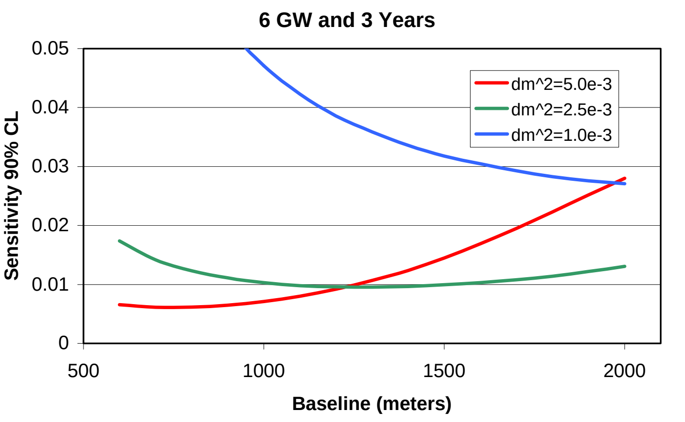
Allowing the variation of:

- reactor power
- run time
- detector size
- reactor capacity factor
- near and far baselines
- background rate
- background sensitivity
- fixed or movable
- fraction time for cross calibration
- one or two reactor scenarios

Sampling of Scenarios

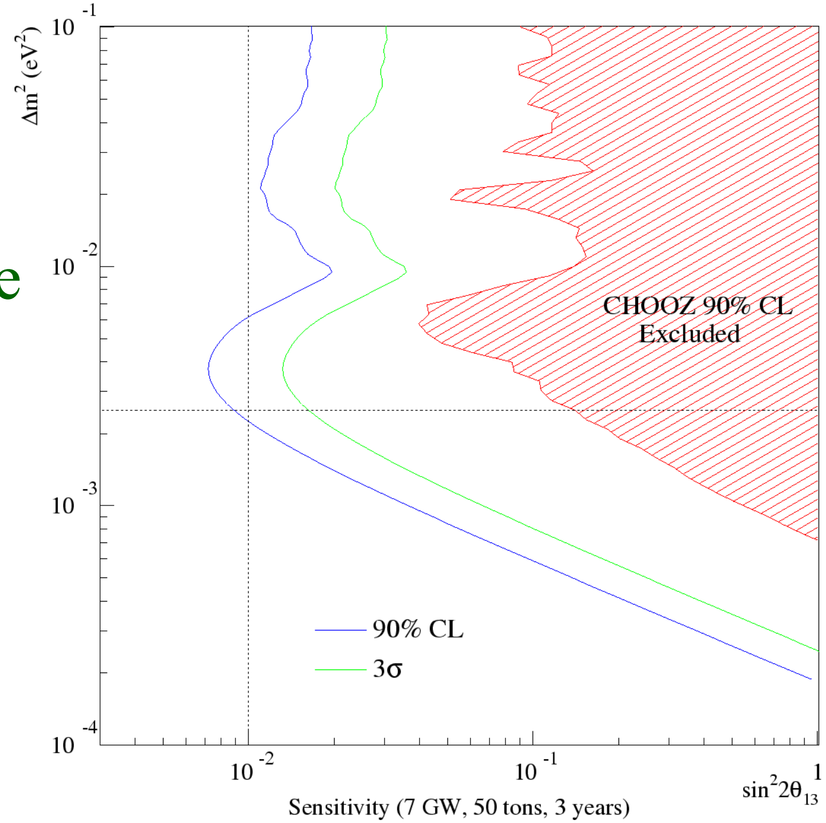
Single Reactor Sites									
Near BL	Far BL	Power	Mass	Depth	Fractional	Type	Years	dm^2=0.0025	
					Uptime			90% CL	3 sigma
150	1200	3.2	50	300	0.962	movable	3	0.023	0.042
150	1200	3.2	50	600	0.962	movable	3	0.018	0.033
150	1200	3.2	50	300	0.962	fixed	3	0.03	0.056
150	1200	3.2	50	600	0.962	fixed	3	0.027	0.049
300	1200	3.2	50	600	0.962	movable	3	0.023	0.042
150	1200	3.2	50	300	0.962	movable	15	0.01	0.018
150	1200	3.2	50	600	0.962	movable	9.5	0.01	0.018
150	1200	3.2	50	n/a	0.962	fixed	infinite	0.021	0.038
300	1200	3.2	50	600	0.962	movable	15	0.01	0.019
Two Reactor Sites									
Near BL	Far BL	Power	Mass	Eff Depth	% Err BG	Type	Years	dm^2=0.0025	
								90% CL	3 sigma
150	1200	6.1	50	300	10	movable	3	0.025	0.0457
150	1200	6.1	50	6000	50	movable	3	0.0104	0.0192
150	1200	6.1	50	6000	50	fixed	3	0.023	0.042
300	1200	6.1	50	6000	50	movable	3	0.014	0.026
300	1200	6.1	50	6000	50	fixed	3	0.025	0.046
150	1200	6.1	50	infinite	undefined	movable	3	0.0089	0.0162
150	1200	6.1	50	30000	50	movable	5	0.007	0.0128





Conclusions and Prospects

- The physics of $\sin^2 2\theta_{13}$ is interesting and important.
- An international proto-collaboration has been formed to work towards a proposal by 2005 (and a white paper this fall).
- The search for a suitable reactor site is underway.
- Controlling the systematic errors is the key to making this measurement.
- Reactor sensitivities are comparable off-axis and the two methods are complementary.
- With a 3 year run, the sensitivity in $\sin^2 2\theta_{13}$ could reach 0.01 (90% CL) at $\Delta m^2 = 2.5\times10^{-3}$.



Institutions of the Proto-Collaboration

Fermi National Accelerator Laboratory

ARGONNE NATIONAL LABORATORY

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Berkeley University of California

THE UNIVERSITY OF CHICAGO

COLLÈGE DE FRANCE 1530

BERKELEY LAB

THE UNIVERSITY OF ALABAMA

MIT

RUSSIAN RESEARCH CENTRE KURCHATOV INSTITUTE

UCLA

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cea

STANFORD UNIVERSITY

Max-Planck-Institut für Kernphysik Heidelberg

UNIVERSITY OF MICHIGAN

TOKYO METROPOLITAN UNIVERSITY 東京都立大学 大学院理学研究科 物理学教室

TUM Munich

We are open to new collaborators…

THE UNIVERSITY of TENNESSEE

K-State Kansas State University

Bologna INFN Istituto Nazionale di Fisica Nucleare

TOHOKU UNIVERSITY

Louisiana State University LSU

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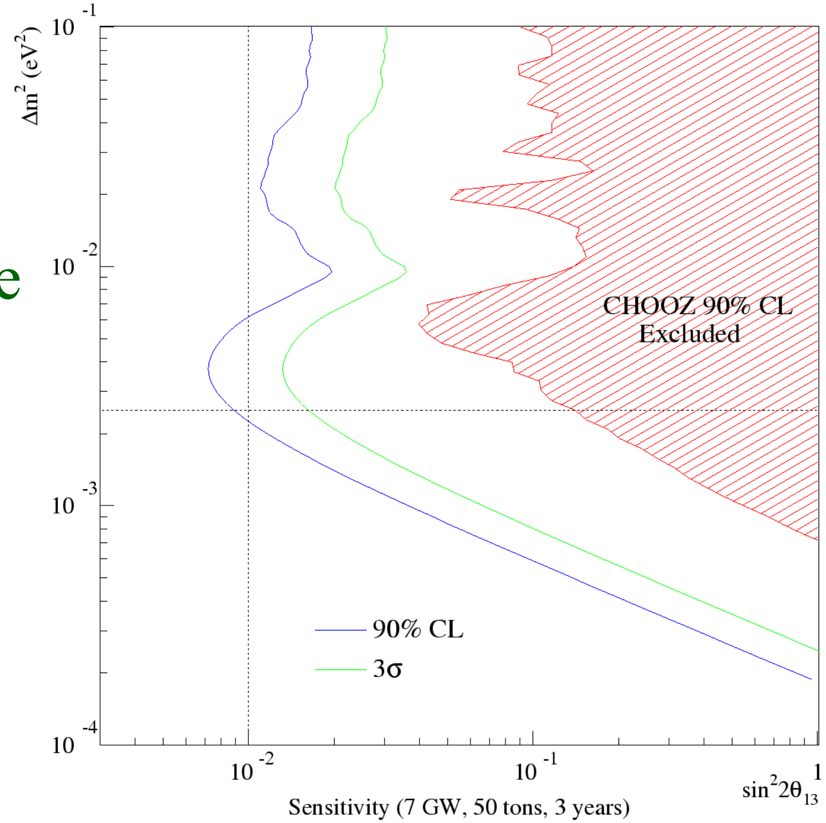
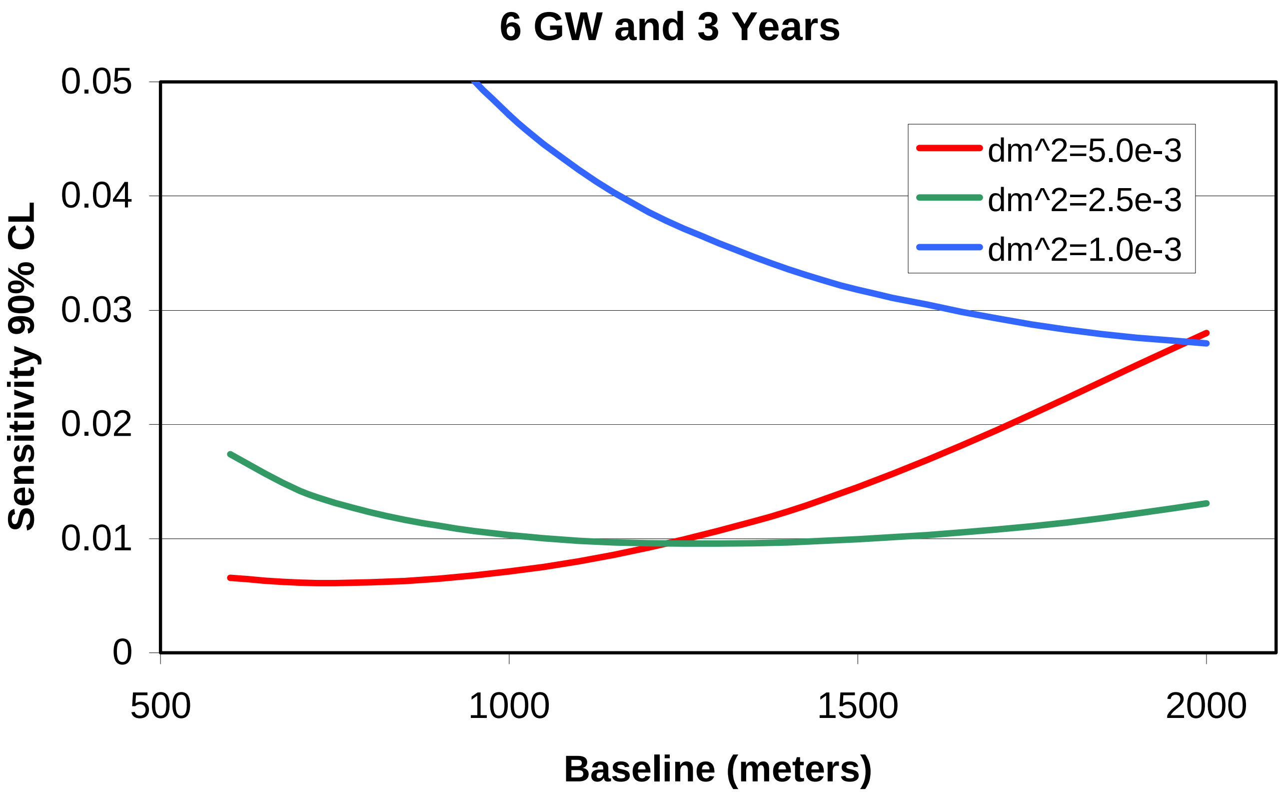


Question Slides

Optimal Baseline



One must consider both the location of the oscillation maximum and statistics loss due to $1/r^2$.

At $\Delta m^2 = 2.5\times10^{-3}$ the optimal region is quite wide. In a configuration with a tunnel connecting the two detector sites, one should choose a far baseline that gives the shortest tunnel (~1200 meters).

Reactor Sites Around the World

Two Reactor Sites

Reactor Site	Country	Avg GWth	Max GWth
South Texas Project	US	6864	7600
Civaux	France	6799	9135
Chooz	France	6795	8872
Gundremmingen	Germany	6734	7865
Braidwood	US	6491	7172
Vogtle	US	6456	7130
Byron	US	6442	7172
Browns Ferry	US	6377	6916
Limerick	US	6365	6916
Isar	Germany	6313	6985
Peach Bottom	US	6290	6916
Sequoyah	US	6209	6822
Penly	France	6197	8088
Philippsburg	Germany	6187	6976
Susquehanna	US	6161	6978
Golfech	France	6136	7977
Catawba	US	6116	6822
Nogent	France	6111	7977
San Onofre	US	6061	6876
Diablo Canyon	US	6043	6749
Comanche Peak	US	5986	6916
St. Alban/St. Maurice	France	5910	8082
Neckar	Germany	5881	6452
McGuire	US	5880	6822
Flamanville	France	5879	8088

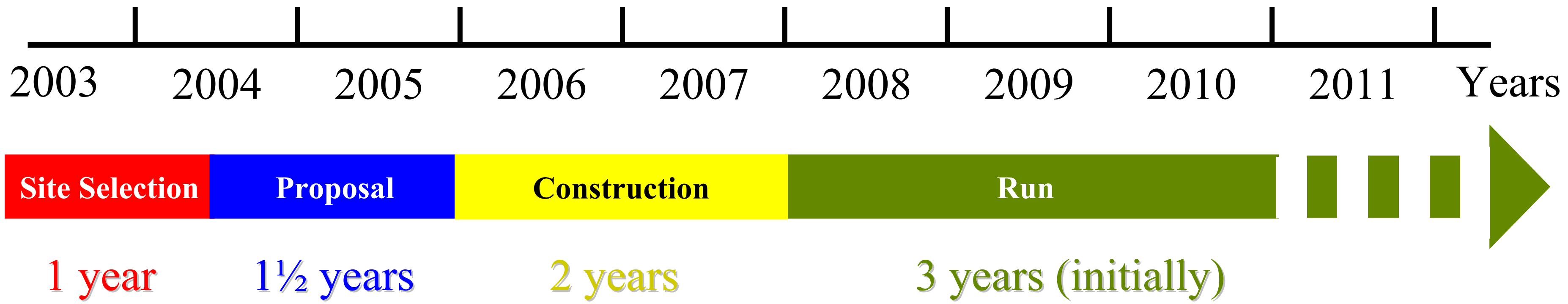
Multi-Reactor Sites

Reactor Site	Country	Cores	Avg GWth	Max GWth
Kashiwazaki-Kariwa	Japan	7	20302	24029
Yonggwang	S. Korea	6	16393	17264
Gravelines	France	6	12458	16696
Zaporozhe	Ukraine	6	12202	17557
Catternom	France	4	12113	15942
Paluel	France	4	11901	16176
Ohi	Japan	4	11269	13782
Palo Verde	US	3	10570	11552
Fukushima II	Japan	4	10384	12875
Fukushima I	Japan	6	10181	13741
Darlington	Canada	4	9028	10932
Chinon	France	4	8653	11166
Blayais	France	4	8644	11131
Cruas	France	4	8586	11190
Takahama	Japan	4	8439	9925
Genkai	Japan	4	8330	10177
Kori	S. Korea	4	8314	9203
Ringhals	Sweden	4	8307	10841
Tricastin	France	4	8284	11178
Bruce	Canada	4	8080	10710
Tihange	Belgium	3	8075	9127
Hamaoka	Japan	4	8031	10584
Forsmark	Sweden	3	7773	9408
Dampierre	France	4	7753	10967
Bugey	France	4	7728	10897

Under Consideration

Former Host Site

Experiment Timeline



Site Selection: Currently underway.

Proposal Phase: Secure funding from government agencies (NSF and DOE)

Construction Phase: Tunnel construction and detector assembly

Run Phase: Initially planned as a three year run. Results or events may motivate a longer run.

Significant Contributions to the Sensitivity

1. Statistics in the far detector

$$\sigma_{stat} = \frac{\sqrt{N_{far} + N_{bg}}}{N_{far}}$$

2. Uncertainty in the relative efficiency of the near and far detector

$$\sigma_{\varepsilon} = \sqrt{\frac{2}{N_{near} f}} \quad \text{(with movable detectors)}$$

where *f* is the fraction of run time used for cross calibration

3. Uncertainty in the background rate in the far detector

$$\sigma_{bg} \cong \frac{\sigma_{bg\ \ rate} \times N_{bg}}{N_{far}}$$

Byron, Illinois

A Possible Site Configuration